N76-19456

APPLICATIONS WORKSHOP III-B-5

THEORY AND FORCE GENERATION

Dr. Lon E. Bell, Technar, Inc., Chairman
Workshop Consultants: C. Mark Percival (SL); Dean Gladow (RTI); and F. R. Norwood (SL)

COEFFICIENT OF FRICTION AS A DESIGN CRITERION

Chairman Bell began the workshop session by clarifying his remarks on coefficient of friction made at the first day's meeting. "I would like to put into perspective what I meant by my remarks yesterday on the coefficient of friction. There are two classes of rolamite devices. In one, rolamite is used in a system with an external load on the rolamite. One of the rollers has an extension, and a table, or the like, rides on the roller. As the table and roller cluster move back and forth, there will be friction. The question becomes, what is the ultimate coefficient of friction of the system? That is, how hard do you have to push on the table (compared to the table weight) to make it move? Therefore, we are interested in the ratio of the load to the force required to move the load; or the coefficient of friction of the system.

"In the second class of rolamites--devices that are not suspension systems, but complete within themselves, such as rolamite switches or pressure transducers--all we ultimately care about is how freely the cluster moves back and forth. That is the criterion that is going to be tied to design specifications.

Naturally, to design the device to meet specifications, we do care what the coefficient of friction is, but what we ultimately care about is the resultant freedom of motion. The mere fact that the rolling friction is small may or may not make rolamite attractive in particular cases where free motion is required."

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EFFECTS OF NON-PARALLEL GUIDES

The effects of nonparallel guide surfaces on angle of repose interested James Means. Percival pointed out that, if the channel undulates or varies in cross section, the angle of repose changes, and so the band length needed to keep the geometry at a certain tightness also changes. There are two cases: (1) a loose geometry where the band just flexes, and (2) a tight geometry that either binds the cluster, or, if slippage and relative motion are allowed, where a combination of sliding and rolling can occur as the cluster moves through the channel.

Also, when the angle of repose changes, the normal force changes. Theoretically, the normal force becomes infinite as the angle of repose approaches 90 degrees.

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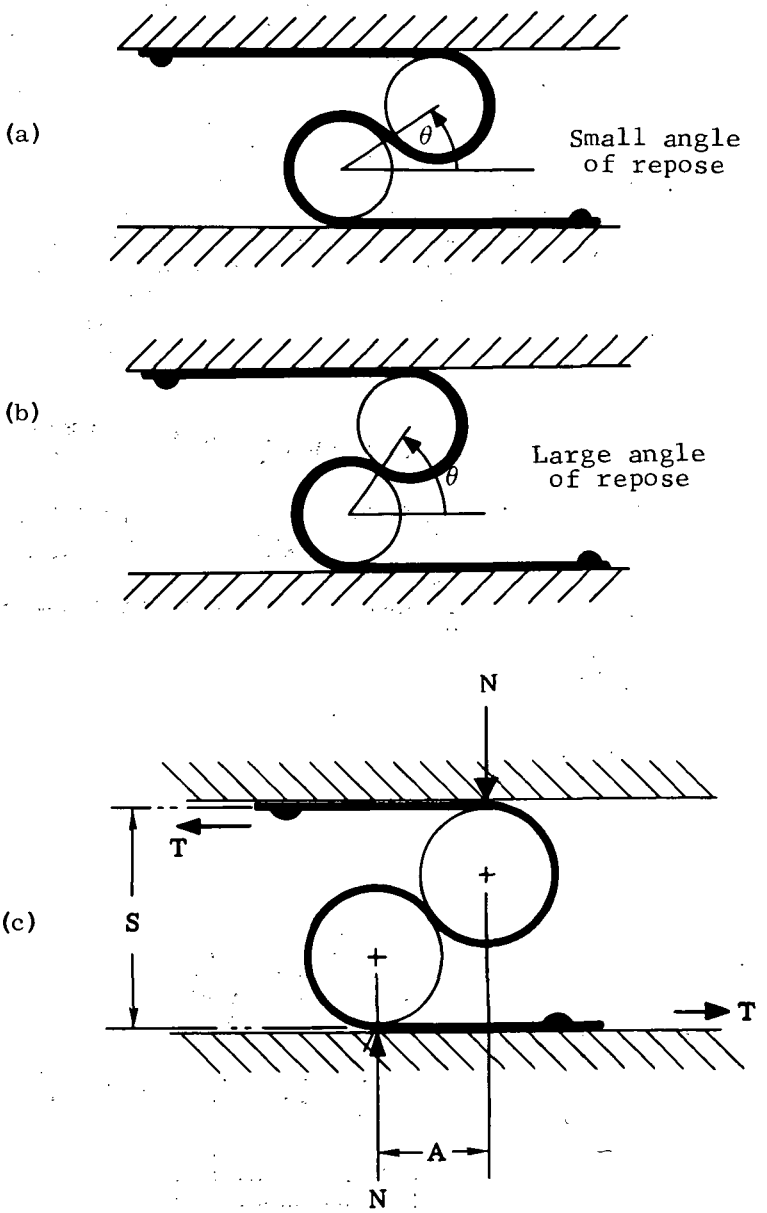
ANGLE OF REPOSE

Gladow remarked on the extreme importance of the angle of repose. Two limiting conditions exist: first, where the rollers very nearly fill the channel; and, second, where they are very nearly on top of each other (Figure 1). The angle of repose is defined as the angle between the centerlines which, of course, goes from very nearly zero to very nearly 90 degrees. The basic formula (the "F equals MA" of rolamite design) is TS = NA. T is the band tension, S the guide surface separation, A the distance between roller centerlines, and N the normal force the rollers exert on the guide surfaces. Naturally, the angle of repose, θ, can be written in terms of S and A.



TS = NA

Figure 1. Basic Relations and Extremes of the Rolamite Geometry

If T and S remain constant, and A is changed (so that the roller diameter changes from a value essentially that of the distance between the guide surfaces S to one-half S), the normal force changes from a lower value of T to an upper value of infinity. Of course, this affects the over-all frictional situation; it affects how much load it can support from the side; and it affects the ability of the cluster to roll over obstructions, machine marks, and contaminants in the system.

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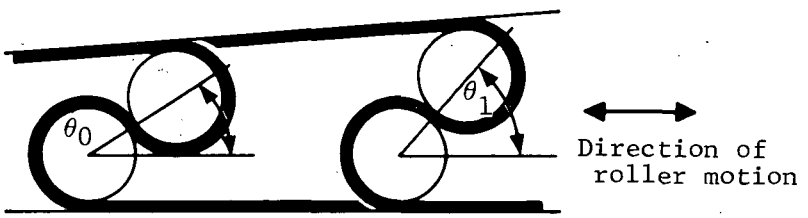
FORCE GENERATION WITH NONPARALLEL GUIDES

Percival pointed out that generation of forces results from nonparallelism of the guide surfaces, as in Figure 2 (a). "If you want to generate large forces along the axis of the rolamite, consider tapering the guides. Use a good stiff band and then lock up the system with high band tension. You will find that if you push the rollers to one end and then take your finger away, the rollers come back at a rapid rate. I used a large, rather stiff spring on the end of the band, to give some compliance. As I pushed the roller into the tighter section of the guide surface, the extra band needed for the larger wrap angle was obtained by stretching the spring. It did not take much motion of the spring to give quite a bit of motion in the roller."

(a)



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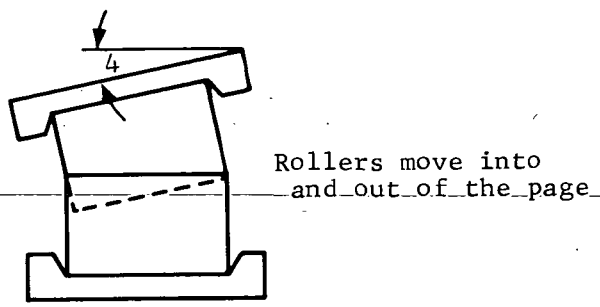

Figure 2. Two Types of Guide Parallelism

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EFFECTS OF GUIDES NONPARALLEL TO THE AXIS

A second type of parallelism or nonparallelism was described by Bell--the guide parallelism along the roller major axis (Figure 2). In this case, band tension tends to rotate the rollers so that they are not properly aligned with respect to the direction of motion. There is a side component of motion which must be opposed if the rollers are to move in the desired direction. The opposing force comes from the rollers contacting the guide surfaces; the rollers slip on the guides and rub at the point where the rollers contact the guide surfaces, resulting in frictional losses. Some calculations indicate that the losses are proportional to α, the angle the top guide makes with the bottom guide, the band tension. The losses are also a strong function of the angle of repose.

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COMPARISON OF TYPES OF NON-PARALLELISM

As Percival summarized it, "there definitely is a difference between the two types of parallelism discussed. One type does not show up as frictional losses but rather as force generation. On the other hand, the second type requires that the rollers move while skewed to each other--sliding has to occur both perpendicular to the axis of motion and on the guide rails. As to the magnitude of parallelism, the best that I can say is that we typically try to hold about 0.2 percent across the width, and about the same along the length. You might be able to live with force generation in one direction, but not a friction."

Nonparallelism of the first sort can be mitigated with spring-mounted bands.

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GUIDE RAIL HEIGHT

Guide rails are necessary to absorb side loads. Also if there were no guides and the rolamite were operated on its side with a loose geometry, the rollers could fall away.

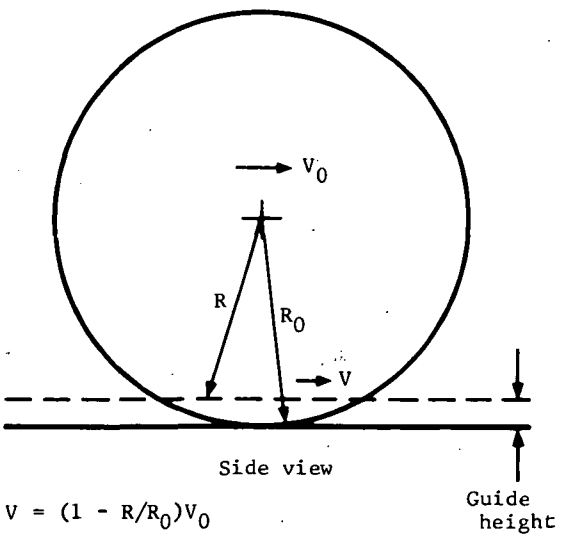

Figure 3. Relative Velocity at Point Where Guide Touches Roller

Dean Gladow illustrated the phenomena that are occurring on the rail. "Obviously, the center of the roller is moving along at the velocity of the roller cluster. On the other hand, the velocity of a point in contact with the guides has no forward velocity at all (Figure 3). Therefore, to keep the total friction at a very low value, use side rails only where there is very little velocity, so that there will be very little energy loss. This means that the height of the rail should be as small as possible compared to the roller diameter. Typical values I have seen used are about 1/30 of the roller diameter. As for the actual shape, I think it is pretty obvious that there can be some relative motion between the guides and rollers, so we try to come up with a shape that keeps the rollers toward the center."

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GUIDE RAIL SHAPE

Lon Bell pointed out that the corner shape on the guide rail is a very important design consideration. "If the guides have a radius at the corner, and the band and roller contact the guide at this point, the band can experience stresses appreciably higher than the stresses associated with bending the band around the rollers. As a result, the band is likely to fail at this point. One technique we use to prevent stress concentrations at this point is to undercut the radius (Figure 4).

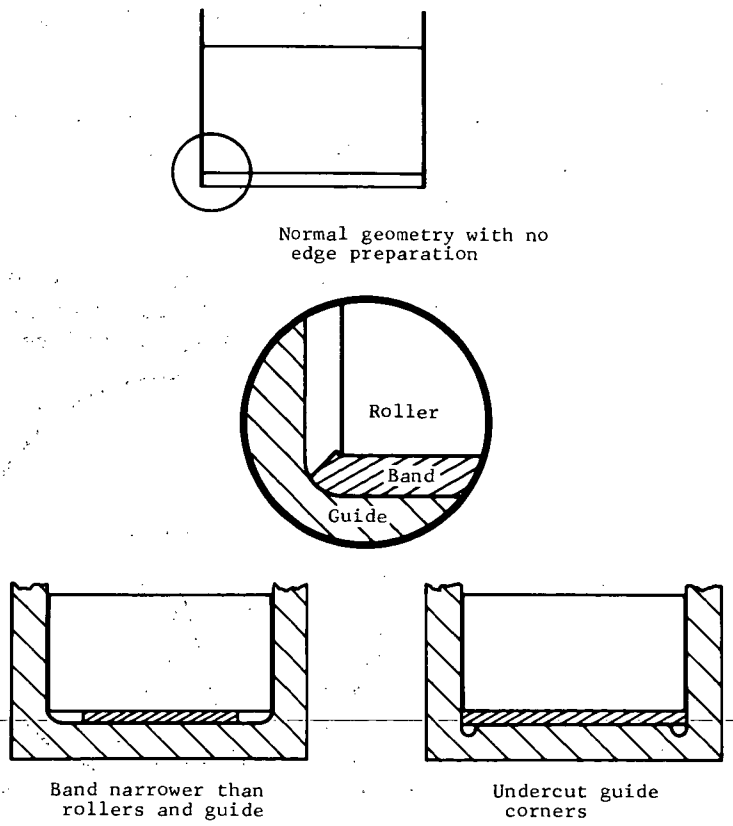

Figure 4. Methods of Eliminating Bending Stresses at the Edge of the Band

However, the undercut is hard to make on small, precise devices. A second solution is to make the band narrow compared to the guide width so that the band does not contact the roller at the corner. Finally, the band can be attached to the roller to prevent the band from coming in contact with the corner." J. M. Fowler pointed out that when the corner is perfectly square, any skewing will cause the rollers to gouge into the side rail and lock.

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BAND WIDTH

In reply to a question of band width compared to roller length, Dean Gladow answered, "We have made bands wider a time or two, but only in very specialized applications. I would say that usually you make the band smaller than the roller. Of course, the interesting thing about Lon Bell's idea of not making the band as wide as the roller is that a guide radius equal to the band thickness can be accommodated. Naturally, the rollers can be contoured as well. However, when you do this, you get into secondary effects such as increased rubbing.

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RTI HINGE APPLICATION

Replying to questions about RTI's application of rolamite as a door hinge, Dean Gladow discussed design. "The door had rollers 1/2 inch in diameter and the guides were 3/4 inch apart. Now, if the door opens a maximum of about 120 degrees, the rollers also rotate 120 degrees (Figure 5). The interesting thing to note is that the band was designed to wrap about 250 degrees around the rollers. But since the rollers only move 120 degrees, there are 150 degrees of wetted perimeter where the band never leaves the rollers. An obvious means, then, of keeping the rollers in position is to put a pin through the band onto the rollers.

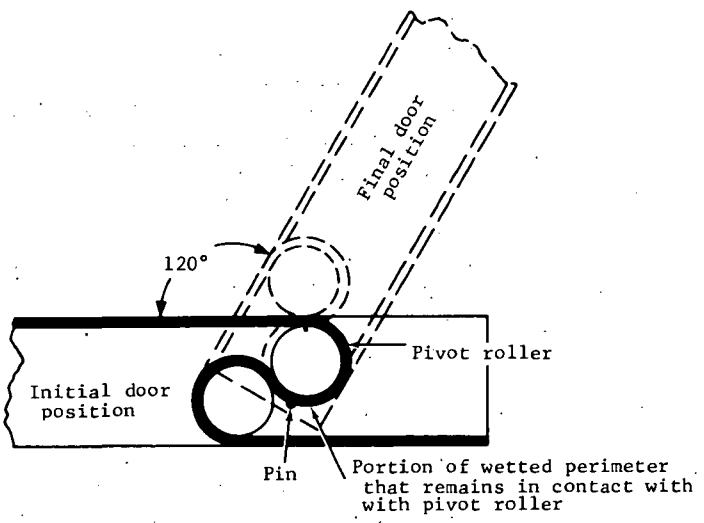

Figure 5. Door Geometry Showing Placement of Holding Pins

"The pin through the pivot roller and the band supports the door, and a second pin supports the auxiliary roller, so that things cannot slide up and down. If you can use it, pinning or spot-welding the band to rollers is a very convenient means of holding rolamite elements in place. Band tension could hold the rollers in place, with the proper tension. I think over a long lifetime you probably would find microslippage, although very little slippage would occur in one traverse.

"I am sure moment on the rolamite as a result of the dead weight of the door load affects the diameter of the pin. The door hinge was not a finished design, and I have not calculated stress loads on the band or the pin."

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BAND TENSION ON PINNED ROLLERS

When a band is pinned to the roller, tension at each end of the band is not of equal magnitude. However, after a device of this design is operated a few times, the tensions equalize.

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COEFFICIENT OF FRICTION VERSUS BAND TENSION

Robert Demers referred to Mark Percival's tests of coefficient of friction versus band tension for different thicknesses of bands. "I could not see much correlation between the curves, especially for the 1-mil-thick band which seemed to go in the opposite direction of the other thicknesses. Is there any reason for that?"

Percival replied, "I think the 1.5-mil-thick results differed by about 25 percent from the rest. The data presented were limited as far as friction data were concerned. Usually, results are taken over a period of months and then averaged. As mentioned earlier, sufficient time had not elapsed to redo the experiments to see how reasonable and consistent our data really are. I think the variations are acceptable as far as friction measurements are concerned. There was a factor of about 2 in the coefficient of friction from the lowest to the highest value. The variation you mention seemed to be independent of band thickness and of band tension, so I think it was just the scatter of the experiment itself. Intuitively I feel there is no reason why the coefficient of friction should be affected by either band tension or the thickness of the band itself, and this seemed to be borne out in the data presented."

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FRICTION IN ROLAMITE GEOMETRY

The friction that does exist in the rolamite geometry seems to come from a combination of microwelding, elastic deformation of the roller on the surface, and hysteresis effects.

Chairman Bell noted that in contrast to rolling a cylinder down a plate, in rolamite the band acts as an intermediary, transfering stresses or loads from the guide surface to the roller. It does not have a point contact as in a cylinder rolling on a surface. In other words, the band touches the guide surface at a point where the roller does not touch the band.

Mark Percival added, "It was interesting that the coefficient of friction that I measured for the full rolamite device was less than the handbooks give for rolling one cylinder on one plate down an inclined plane, so I think the band is relieving some of the contact pressure you were talking about. You would think, offhand, that rolamite friction would be about four times as great, since there are four contact points, if you consider roller-to-band contacts. Yet the total coefficient of friction is less than for just one roller rolling down an inclined plane. The coefficient of friction is, I think, very much enhanced by remating of surfaces, or maybe we have a cantilevered portion of the band, as you mentioned. As Dick Cadman showed in his talk, the band tends to spread the contact pressure out between the roller and the surface, keeping the contact pressure at a very low value, and increasing the ability of the two materials to roll over each other without sticking or elastically deforming."

Tight geometry does not increase coefficient of friction as drastically as one would expect. For a 1/2-mil band and a 2-mil band, the "tightness" with regard to gap between the rollers is significantly different, yet the coefficient of friction seems to be about the same up to tensions of 6 pounds or so. Yet the roller spacing with the 1/2-mil band is within 1/10 of a thousandth of an inch or so of being a tight geometry.

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HIGH ENERGY FORCE RELEASE

A Sandia device which generated sufficient force to shear rivets was described.

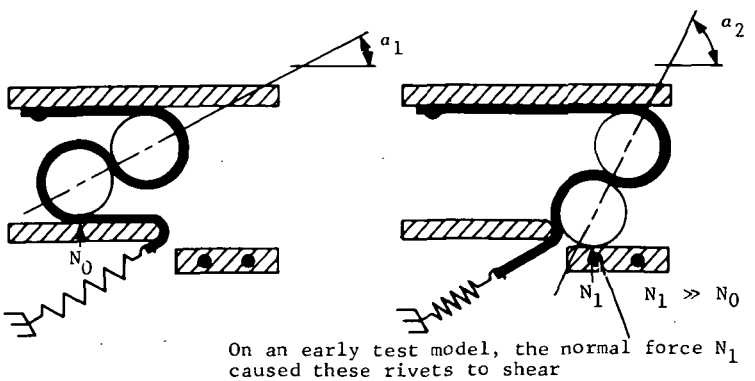

Figure 6. Expanded Channel Rolamite

The normal force is the product TS divided by A. If A is nearly zero where the channel expands, the rollers will generate large normal forces at this point. Expanding the channel can result in very high forces, enough to shear rivets as a result of the expansion.

THEORETICAL FORCE GENERATION MEASUREMENTS

A participant asked whether all variations from theoretical force were due to friction. Dean Gladow replied, "If you plot a complete cycle of motion of a rolamite using a load cell, you will find that the force curve generated looks like the one shown in Figure 7. On the reverse cycle, the curve still has the same shape, but it is displaced by an amount equal to twice the frictional loss in each direction. After hundreds of cycles, the curves are still distinguishable with the same general shape, although the peaks gradually decrease.

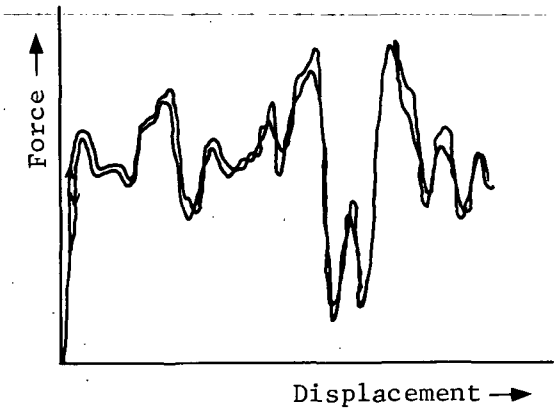

Figure 7. Typical Force Deflection Trace Made With Rolling Friction Test Apparatus

"Several things--machine marks on guide surfaces, localized variations in band thickness, and contaminants which have entered the system--combine to affect details of force generation. I think there is one thing of importance--after hundreds of cycles you are still able to recognize the force curve, but if you loosen the tension and move one roller just one degree, you will get a completely different force curve out of the system."

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BAND SURFACE IMPERFECTION AND NOISE

Dick Cadman conjectured that the noise percentage of the total force ranges from 3 percent to about 10 percent with less carefully controlled tolerances. With good finishes on the guides, rollers, and the band itself, the variation is about 3 percent. The band is of great importance because band thickness is controlled only to about 5 percent accuracy for bands of about one thousandth of any inch in thickness. Since the force is proportional to the band thickness cubed, variations of 5 percent cubed become very important.

The manufacturer's 5-percent tolerance is the variation from nominal of a roll of material, and not necessarily the variations from point to point over a given band. Variations in a roll of material and for different rolls are very important if reproducible force-generating characteristics are sought from one band to the next. Variations of ±5 percent in thickness can

result in force variations of ±15 percent. Also, variations within a band are important for devices that must generate precise forces (or no force at all), since these anomalies add to the noise.

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BAND STRESS FOR ROLAMITE OPERATION

Replying to a question about yield strengths for band operation, Chairman Bell cautioned the participants, "If very few operations are required of a device, and the band must not absorb significant energy from permanent deformation, the material should be stressed at or below the 0.02 percent offset strength. Unfortunately, only the 0.2 percent offset yield is generally tabulated. For most materials, this stress should be derated by about 10 percent as an operating limit. On the other hand, if you want single operation and the force generation capabilities of the band are not important, or if the band is quite thin for the roller size, then the stresses can be closer to the yield stress. For millions of cycles, the band must be stressed below its endurance stress.

"The stresses that can build up in severe environments must be kept in mind, especially for devices that operate millions of cycles. Generally, smooth roller cluster motion is assumed and stresses are calculated from statics. However, the rollers nearly always terminate their motion in one direction by hitting, dropping, scraping, or contacting some barrier that disturbs the geometry or puts localized stresses on the band. Also, if the band has cutouts, stress concentrations result. In either case, if you assume smooth motion and ignore the effects of cutout on stresses, the resultant stress calculations may be way off--often by at least a factor of 2."

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TENSILE, BENDING, AND CONTACT STRESS

William Holliday was interested in accounting for a combination of bending, compressure, and tensile stresses in the band at the point of contact between the rollers or a roller and a guide surface. In his friction work Percival had calculated the combination of tensile stress due to band tension and bending stress. "I tried to work in tensions on the band that were below 50 percent of the yield stress, to get away from stress concentrations, plasticity, or any other side effect that would modify the band's behavior. I do not know if anybody has really considered contact stresses in the design of rolamites themselves for production. My interest was mainly in making sure that the experiment, as performed, was as close to an ideal geometry as possible. With regard to contact stresses at points of impact, I did notice in our tests, where the band and rollers fall 1/2 inch and impact on a solid stop, that after 40 or 50 actuations the band permanently deformed to such an extent that you could see the damage to the band."

STRESS LEVELS

Gladow's experience led him to comment that stresses become important in two situations: upon cluster impact and in geometrics where the angle of repose is very nearly 90 degrees. If neither of these situations exists, the stresses are typically very small, compared to the tensile stresses and flexural stresses in the band. For example, in normal bearings stresses range from 100,000 to 500,000 psi, while typical stresses in the normal rolamite are from 300 to 10,000 psi (with the angle of repose less than 75 degrees and no impact). Even the higher stress is only 3 percent of the yield strength of most band materials.

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BAND MATERIALS

The primary disadvantage in using soft materials, such as plastics, for bands, is that they creep or set after a given time. Then, if the cluster is moved, it tends to return to its original position. Secondly, forces generated by band cutouts or preform are not as high as with metals. Plastics are very valuable in mock ups or prototype models, but probably finished devices will be using metal bands.

Some very high-strength aluminum alloys become interesting for applications where force generation is not important. Bell pointed out that the governing parameter in this case is the ratio of the yield stress or endurance stress divided by Young's modulus. Since, for aluminum and some magnesium alloys, Young's modulus is very low, this ratio can be quite high. This ratio, called the flexivity, determines how thick a band can be wrapped around a roller of a given diameter.

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LOW FRICTION DEMONSTRATION

In a discussion of energy losses in rolamite as qualitatively observed by several participants, Norwood described a Sandia device. "When a large model with 3- or 4-inch roller diameter, two hollow aluminum rollers, and a 5-mil uniform Mylar band was placed on a level table, the rollers would roll in a given direction. If you turned it around, the rollers would stay at that end, which gave you the feeling that the table was flat and not affecting their motion. And yet, when the whole device was turned over, they rolled back. What was happening was that when the band was at the top (Figure 8), it was at a higher potential energy state than when it was on the bottom. The potential energy difference due to the change in band elevation (or the band weight) was enough to make the rollers roll.

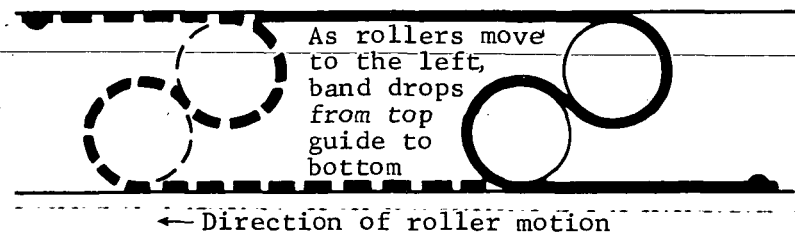

Figure 8. Effect of Band Weight on Roller Position